An Agent-based Model of the World Energy System Using a Biophysical Economics Perspective

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Abstract

There are concerns whether the world energy system (WES) can supply sufficient energy for societies. Dealing with such threats for the societies and economies needs scientific solutions. Scientists develop models in order to gain better insights into the system. Most existing global energy supply models adopt a top-down view on the WES. The top-down view assumes that all elements of the system have global knowledge about it. It cannot capture some characteristics of WES such as geographical resource and demand diversity. In addition, it is not possible to analyze the emergent effects of variations in low-level elements on the system behavior in top-down analysis. This article develops an exploratory agent-based model to for bottom-up analysis of WES as well as considering limitations of natural resources. The Multi-Region World Energy Model (MRWEM) is developed by combining GEMBA, an existing biophysical economics model, with the concept of EROI for imported energy. The model provides insights on the global and regional behaviors of the WES. The model results suggest that under MRWEM assumptions, non-renewable energy production in the world will peak and decline. Energy trade can experience the same pattern. In addition, the gap between energy requirements of societies and energy supply can increase and renewable are not likely to fill the gap.

Key Words: Agent-based model, World Energy System, Biophysical Economics, Energy Trade, EROI

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1 Introduction

Energy can be considered as an essential factor in human life. It can be obtained from renewable and non-renewable resources. Currently, non-renewables are dominant resources in world (IEA, 2012). Since these resources have finite size, there are concerns about future of world energy supply. In 1956, Hubbert predicted that oil production would peak in 1970 in US by fitting a curve to cumulative oil production (Hubbert, 1956).The Hubbert curve, which later proved to be accurate (Nashawi, Malallah, & Al-Bisharah, 2010), caused concerns about the rate of energy production and, in turn, future scarcity of energy resource especially oil. This can be a dire threat for the future of the world. Dealing with this threat for the economies needs scientific solutions.

To gain a better understanding of the world energy system, scientists attempt to make models in order to find rules that govern the system and to explore possible futures. Modeling is "a way of solving problems that occur in the real world. It is applied when prototyping or experimenting with the real system is expensive or impossible" (Borshchev & Filippov, 2004). In his review of the global energy supply models, M. Dale (2010) classified existing models in the literature into three categories of "deterministic models with growth curves" (e.g. Hubbert curve), "energy-economy optimization models" (e.g. WEM, MESSAGE, and MARKAL), and "physical resource accounting models" (e.g. WORLD3). However, most existing models of the world energy system to this date have a common problem. They adopt a "top-down" view for analysis of energy supply in the world.

Top-down view assumes that there is a centralized control over the system and all elements have global knowledge of the system (Crespi, Galstyan, & Lerman, 2008). However, the world energy system (WES) is in essence a decentralized system with many physical elements and actors. In addition, the top-down view prevents the analysis of the effects of micro elements of the systems and their interactions on the holistic emergent behaviors of the system. To obtain such insights, a bottom-up view is required. In case of WES, the bottom-up approach can also enable geographical analysis of the system. Therefore, there is a need for a model for the world energy supply which adopts a bottom-up view and considers the limitation of natural resources. Agent-based modeling (ABM) is a modeling approach used to study social systems that views the system from bottom-up and is made up of interacting autonomous (Janssen, 2005). ABM can also capture other characteristics of the world energy system such as instability and dynamics and allow the consideration of geographical dependencies of this system.

The objective of this article is to develop an agent-based model in order to explore the behaviors of the world energy system (WES) with bottom-up view. It also attempts to incorporate limitations of natural energy resources. Another purpose of the model is considering energy interactions and trade among multiple geographical regions of the world in the modeling and exploration process.

This article is structured as follows: In section 2, the methodology for developing the agent-based model will be explained. Having the theoretical perspective and modeling approach set, section 3 elaborates on the design of the agent-based model. In this section, the conceptual model will be provided. In section 4, the results of the model will be presented and analyzed. Finally, in section 5, the modeling process will be reviewed and the main conclusions will be presented.

2 Methodology

This section discusses the theoretical perspective of this research; biophysical economics, and agent-based modeling as the modeling approach. In sub-section 2.1, the definition of biophysical economics, its advantages over standard economics, and its view on the world economy will be provided. The definition of ABM and its requirements will be explained in section 2.2.

2.1 Biophysical Economics

"Biophysical economics is a system of economic analysis that is based on the biological and physical properties, structures and processes of real economic systems as its conceptual base and fundamental model" ((C. Hall & Klitgaard, 2006), quoted from (Howard T Odum, 1971)). In biophysical economics, the role of natural resources in the economic processes is highlighted.

Currently, the standard (mainstream) economics considers the world as a closed system in which firms and households exchange goods and services with factors of production (Sloman, 2006). However, this theory has some drawbacks. For example, it violates laws of physics and thermodynamics. According to the first law of thermodynamics, low entropy resources which enter the economy system should be degraded and leave it as waste (Ayres, 1978). However, it is in contradiction with the closed system of economy in standard economics. Another drawback of standard economics theory is the boundary of the economy system. It does not consider the fact that the economy extract natural resources and send wastes to the environment (C. A. S. Hall & Klitgaard, 2012).

Contrary to standard economics, biophysical economic incorporate the natural resources and pollutants in the analysis. Figure 1 illustrates the biophysical model of the economy. It shows how the main economy (in definition of standard economics) is linked with the environment. In addition, following the work of H.T. Odum (1971), it shows a counter flow of money and energy in the main economy. The wastes (pollutants) also exist in the model.

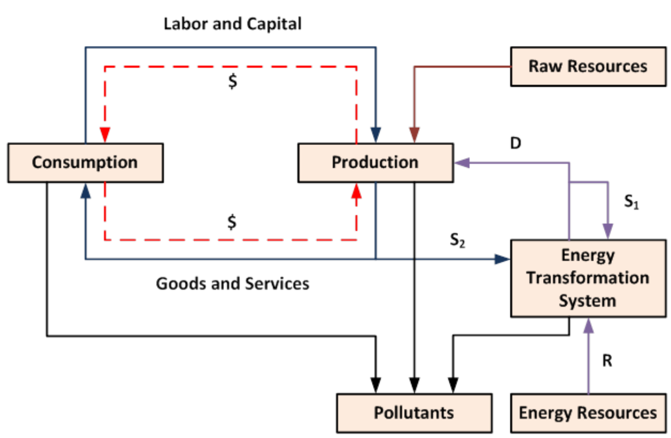

Figure 1 The biophysical systems model of the economy from (Gilliland, 1975) – Picture from (M. Dale, 2010)

In Figure 1, letters *D*, S_1, and S_2 can be used for measuring the energy-return-on-investment (EROI). EROI is one of the most important measures in biophysical economics. It can influence the production from resources. It can also provide signals for investment in different energy options. EROI is the ratio of energy returned from an energy-gathering activity compared to the energy invested in that process. EROI can be calculated as:

$$EROI = \frac{D}{S_1 + S_2} \qquad Eq.1$$

Figure 1 shows the biophysical view of the world. However, at higher resolutions, other concepts such as energy trade can be considered. For, incorporating energy trade in biophysical analysis, it is necessary to calculate EROI of trade. In practice, there are some difficulties for measuring the EROI of trade. It is because of difficulty in measuring the flow of capital (investment) in return of which the energy is yielded. However, Kauffman (1986.) proposed a method to estimate EROI of imported energy with incorporating energy price and energy intensity of the importing country. In this approach, EROI of trade can be measure according to following formula:

$$EROI_t = \frac{E_{boe}}{E_{\text{intensity,t}} * P_{boe,t}} \qquad Eq.2$$

where E_{boe} is energy content of a barrel of oil equivalent (6164 MJ/boe), $E_{\text{intensity,t}}$ is energy intensity of the economy in year t (MJ/USD), and $P_{boe,t}$ is the price of a barrel of oil equivalent in year t (USD). In the definition of biophysical economics which is illustrated in Figure 1, the energy trade takes place between energy transformation system of exporting country and main economy of importing country.

The objective model of this research adopts the rules of GEMBA, one of the newest biophysical economics models in the literature. It is developed by M. Dale (2010). In the remainder of this sub-section, GEMBA will be introduced.

2.1.1 GEMBA

GEMBA stands for “Global Energy Modeling - A Biophysical Approach”. It is a system dynamics model for exploring the global energy supply (M. Dale, 2010). It decomposes the world into two sectors: energy sector and the consumer sector of the rest of economy(M. Dale, Krumdieck, & Bodger, 2012). The energy sector contains two types of resources: renewables and non-renewables. Energy sector needs inputs of fuel and capital for operation. “Capital intensity” and “fuel intensity” are the ratio of each input over total input. Capital intensity of renewables is far higher than non-renewables in GEMBA.

In GEMBA, the main stocks are non-renewables resources, energy sector capital, and consumer capital. The main flows are accumulation and deprecation of capitals, rate of extraction of non-renewables, and rate of production of renewables. The cumulative non-renewable production is limited by “ultimately recoverable resource” (URR), and the rate of renewable production is limited by “technical potential” (TP).

GEMBA considers the “ratio of cumulative non-renewable extraction over URR” and the “ratio of yearly produced renewable over TP” as measures of energy availability (M. Dale et al., 2012). In addition, considers EROI as a measure for energy accessibility within WES. It employs a dynamic function for calculation of EROI. It has two components of “technology progress” and “resource quality” (Michael Dale, Krumdieck, & Bodger, 2011). Both components are functions of energy availability. In the dynamic EROI function, EROI increases, peaks, and declines at energy availability increases.

EROI influences a number of variables in GEMBA. Energy production from an energy resource is proportional to its EROI. A part of energy production returns to energy sector to enable its activities. It is called “fuel feedback” and it depends on “fuel intensity” of the sector and it is inversely proportional with EROI. The energy sector also receives “capital feedback” from the rest of the economy. The capital feedback depends on the allocated energy demand to a resource. Energy resources compete with each other to get more share of economy’s energy demand. The resources with higher “favorability” receive more shares. Resource favorability is proportional with EROI and negatively proportional with resource availability. When the demand is allocated to a specific resource, the required capital needs to be accumulated in the energy sector. The size of capital requirements depends on “capital intensity” of resources. Also, it is inversely proportional with EROI.

In the main economy, the industrial output is proportional with net energy yield from energy sector (produced energy minus fuel feedback). It also depends on “energy requirement ratio” which refers to energy intensity of the economy. On part of industrial output gets accumulated as consumer capital. The other part returns to energy sector (as capital feedback) to enable operation of this sector. The latter has priority over the former due to importance of energy supply for functioning of the economy. The energy demand is proportional to level of capital in the main economy. It also depends on energy intensity and the “effectiveness of industrial capital”, a measure of the industrial output per unit of industrial capital stock.

More information about GEMBA can be found in (M. Dale, 2010). The relationships among variables cause a complex structure and behavior in GEMBA. However, GEMBA is a system dynamics model and it adopts a top-down view. For considering energy interactions among the world geographical regions and exploring the emergent behavior of WES, a bottom-up view is required. In the remainder of this section, a proper paradigm for bottom-up modeling is explained.

2.2 Agent-based Modeling

“Agent-based modeling (ABM) is the computational study of social agents as evolving systems of autonomous interacting agents”(Janssen, 2005). Agent-based models consist of a number of individuals (agents). These agents have their own states and behaviors. Agents interact with each other. The states and behaviors of whole system emerge from the states and behaviors of agents and their interactions. Agent-based modeling can be used for bottom-up analysis of systems. Therefore, the purpose of agent-based modeling is investigating the effects of individual or local interactions on the emergent behaviors in the system (Scholl, 2001).

In this research, a model of the world energy system will be developed. The model will be designed on the basis of GEMBA and the concept of EROI of imported energy (*Eq.2*). In our model, the world is decomposed into a number of geographical regions. Each region is itself a “world” in GEMBA definition. So, for agents representing regions, GEMBA will be re-implemented and modified in order to facilitate energy trade. Therefore, agents in our agent-based model will inherit all attributes and behaviors of GEMBA whereas they have additional features for energy trade. The development process of the model will be explained in the next section.

3 Multi-Region World Energy Model

The modeling process will be explained in three steps of *design*, *implementation*, and *evaluation*. The design step decomposes the system into a number of interacting agents and defines their characteristics. It also determines how agents should communicate and interact with each other. The implementation step explains how the model was implemented as a computer simulation. The evaluation phase proves the validity and credibility of the model.

3.1 Definition and Design

In Multi-Region World Energy Model (MRWEM), the world energy system includes 11 geographical regions. The 11-region decomposition provided GEA Scenario Database (IIASA, 2012) is used in MRWEM. In MRWEM, each region is decomposed into four sectors on the basis of similarities and differences in states and behaviors. Consequently, each region contains four agents representing these sectors:

1. ***Renewable Supplier*** is the agent representing renewable energy sector in the model. Its purpose is to produce energy and manage renewable energy infrastructure. Its main parameters are TP, capital intensity and parameters of the dynamic EROI function. Its main variables are availability, EROI, production, feedbacks (fuel and capital) of each resource, the level of capital, and the capital lifetime. A Renewable Supplier, produces energy, consumes fuel feedback, accumulates capital, disposes depreciated capital, and updates key variables such as EROI, availability, etc.
2. ***Non-renewable Supplier*** is the agent representing non-renewable energy sector. Its purpose is to produce energy and manage non-renewable energy infrastructure. In general, the attribute and behaviors of Non-renewable Supplier and Renewable Suppliers are the same. The main difference is that a Non-renewable Supplier has parameter of URR instead of TP. This difference if inherited from GEMBA (M. Dale, 2010). It influences the measurement of energy availability. More details can be found in (M. Dale et al., 2012).
3. ***Energy Consumer*** represents the rest of the economy which consumes energy. Its purpose is to produce wealth and capital in the economy and manage different industries and infrastructures. The main parameters of energy consumers are effectiveness of capital, energy intensity, and capital lifetime. In addition, Energy Consumer updates a number of state variables every year. The functions and equations of Energy consumers are extracted from (M. Dale, 2010).
4. ***Energy Dispatcher*** intermediates the flow of energy and capital among energy suppliers and the consumer. Its purpose is aggregated the energy yield for the rest of economy, allocate energy demand to different resources, and facilitate energy trade. Until now, all attributes and behaviors of agent were similar to GEMBA. The main differences in the function are in Energy Dispatchers. The main parameter of Energy Dispatcher is "incept date" of energy sources. Incept date is the year in which a resource becomes available in the system. Also, "URR Index" and "Energy Export" are the main state variables of energy Dispatcher.

Since each region contains four agents, in total, the MRWEM has 44 interacting agents. Figure 2 illustrates the flow of energy and capital among agents in MRWEM. Inspired from GEMBA, renewable and non-renewable suppliers produce energy and receive capital feedback from the energy consumer.

They also provide information about energy availability and EROI for energy dispatchers. Energy consumers receive energy and produce capital for the economy and the energy sector. It also provides information of energy demand for the energy dispatchers. Energy dispatcher aggregates the produced and imported energy for consumption in the economy. It also allocates the energy demand to different energy resources. This allocation influences the distribution of capital feedback among energy resources. It also manages the energy trade.

In order to enable energy trade, another agent is considered in MRWEM, ***Trade Activator***. It is a passive agent which shows the link among regions and provides necessary information for energy trade. Initially, there are two directed links (Trade Activators) between each pair of regions (Energy Dispatchers). However, they can become active by importing Energy Dispatcher. The purpose of Trade Activator is to enable energy trade among regions. It has a number of parameters such as trade distance, trust coefficient, and agent activity. Its main variables are trade EROI, net energy trade, trade favorability and trade accessibility. Following the concept of EROI for imported fuel by Kauffman (1986.), trade EROI in MRWEM is calculated with:

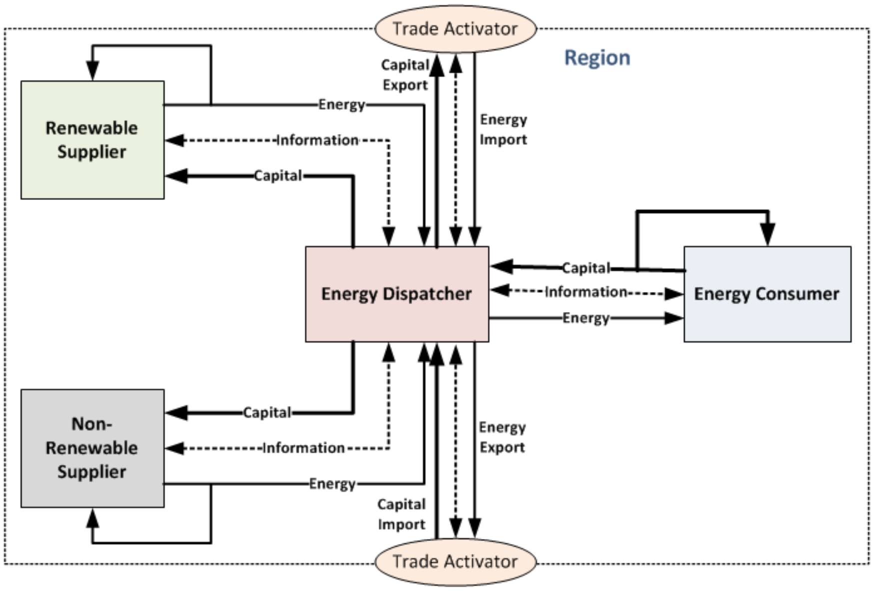

Figure 2 Flows of energy and capital among agents

$$EROI_{trade,t} = \frac{\text{TrustCoefficient} * \text{TradeEROICoefficient} * 6124.046\,(MJ)}{\text{Energy Intensity}\left(\frac{\text{MJ}}{\text{USD}}\right) * P_t(USD)} \qquad Eq.3$$

Where Trust coefficient, trade EROI coefficient, and Energy Intensity are parameters of the model, the P_t represents global energy price. Trust coefficient is a number between 0 and 1 which represent the degree of trust and cooperation among regions. It can influence the perception of regions about trade EROI. Trade EROI coefficient is an scaling factor to make the value of trade EROI comparable with values of dynamic EROI function. In MRWEM, the favorability of trade (for importers) can be calculated as follows:

$$\text{Trade favorability}_t = \left(1 - \text{trade Availability}_{\text{Mean, Non-Renewable, t}}\right) * \text{trade EROI}_\text{t} \qquad Eq.4$$

In addition, in order to incorporate delay in perception of trade favorability, this variable can be smoothed using first order exponential smoothing for last 5 years. Here, trade availability is the mean of availability of non-renewable resources at supplier side. The energy trade is limited to non-renewables. Also, there is a limit on size of energy trade. It is assumed that regions cannot export more that 90% of their non-renewable production.

3.2 Implementation and Evaluation

The MRWEM is implemented in NetLogo. The aggregated value of URR and TP are the same as GEMBA. However, the percentage of URR and TP for each region is derived from GEA Scenario Database (IIASA, 2012). The parameter of dynamic EROI function are calibrated manually through 100 run and parameter change. The initial stocks in GEMBA are distributed evenly among regions in MRWEM. Other parameters in MRWEM are the same as GEMBA.

Similar to GEMBA, the model is run for year 1800-2200. The data for energy price before 2012 is obtained from (BP, 2012). For years after 2012, four scenarios were considered for energy price. Also, for trust coefficient of trade links after 2012, two scenarios of “trust as usual” and “full trust” are examined.

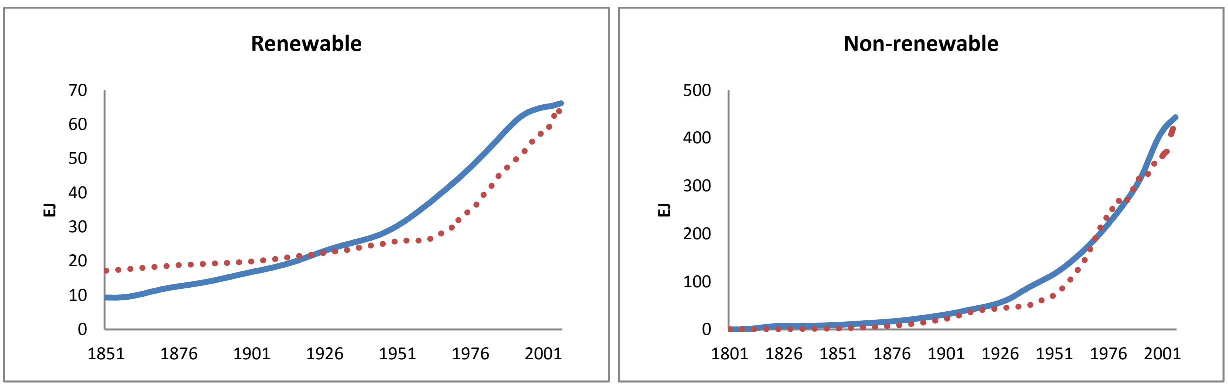

Figure 3 Comparison of model results with historical data (dotted lines illustrate historical data)

The validation of the model was done by historical replay. The model aggregated results are confronted with historical data for renewable and non-renewable production. The historical data used in this work is the same as data in (M. Dale, 2010). Figure 3 illustrates the comparison of total renewable and non-renewable energy production in MRWEM and the historical data. The fitting quality for renewable production is R^2=0.951895 and for non-renewable production is R^2=0.986616.

4 Results and Analysis

In this section, a number of important results of the MRWEM will be presented and discussed. Figure 4 illustrates the value of a number of variables during years 1800-2200. The generic behavior of the dynamic EROI function proposed by M. Dale (2010) shows an overshoot and collapse. This behavior influences the energy production in the model. Figure 4 shows how energy production (especially from non-renewables) can decline. In GEMBA and MRWEM, energy production depends on both EROI and the level of capital in the energy sector. The decline in production of non-renewables (and renewables) shows that the level of capital cannot compensate decline of EROI. It is because the favorability and, in turn, capital investment in energy sector depends on EROI as well. Therefore, on EROI decline, the level of capital decreases as well.

Figure 4 shows the increasing gap between the desirable energy requirement (energy demand) and the total energy yield after the decline in non-renewable production. The model shows that renewable energy cannot compensate the decline of non-renewable energy production. In general, TP of renewables is limited in comparison to URR and the capability of non-renewables for annual production. In addition, in MRWEM, the capital intensity of renewables is far higher than non-renewables. So, if non-renewable resources want to be replaced with renewables, more capital should be invested in the energy sector. It limits the growth of the rest of economy. The fact that the consumer sector cannot provide sufficient capital for renewable energy sector causes a decline in renewable production as well. However, renewables' production descent is not as steep as non-renewables. Renewable production tends to form a plateau rather that converging to zero.

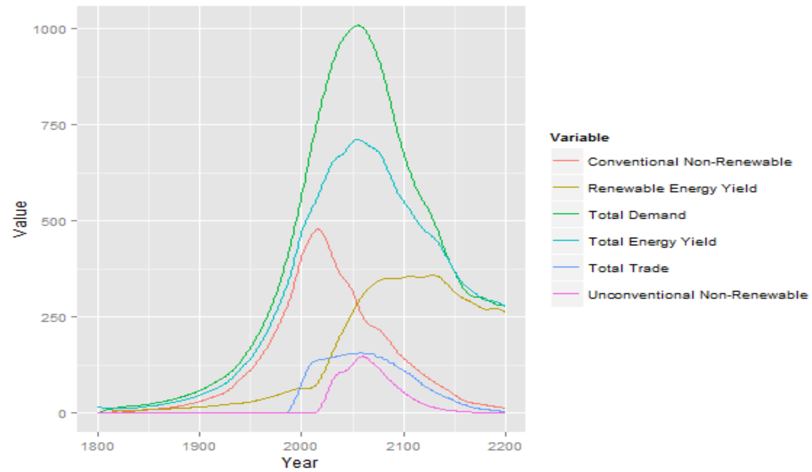

Figure 4 MRWEM Outputs

Another fact in Figure 4 is the increase, peak and decline in energy trade. Since the energy trade in MRWEM is limited to non-renewables, the decline in production of non-renewable results in decline in energy trade among regions. Figure 5.a shows the number of active trade links in energy trade network. It shows that trading links and routes among regions took place in the model after 1950 when the gap between net energy yield and energy demand started to rise. In total, it is possible to have maximum 55 trade links among 11 regions. Figure 5.a shows that by 2030, around 47 links take place in the model and the system becomes stable. In MRWEM, the links do not disappear from the system when they become active. However, the size of trade can become negligible. Figure 5.b shows the size of energy export by different regions. Regions such as MEA (Middle East and North Africa), FSU (Former Soviet Union), and NAM (North America) relatively export more energy than other regions. One important reason is the higher size of URR for conventional oil and gas in these regions.

In addition, Figure 5.b illustrates a number of points in which the curves become non-smooth. It is because of the fact that these regions export considerable share of their non-renewable production. But, since there is limit for energy export, such instability emerges in the system.

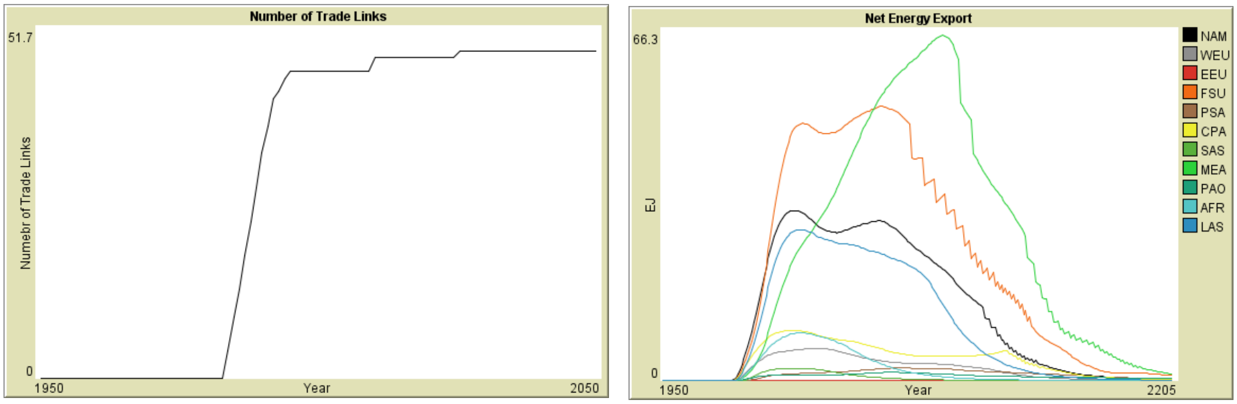

Figure 5 Energy Trade in MRWEM: a. Number of active trade links (routes) b. Size of energy export of each region

Finally, all aforementioned results were based on fixed parameters in the model. As mentioned in *Eq.3*, the EROI of trade in MRWEM depends of energy price, energy intensity of importer, and the degree of trust among regions. This work analyzed the effects of different ranges of parameters for energy price (after 2012) and different scenarios for degree of trust among regions. The results show that although the detail values can differ, the generic emergent patterns for all variables are the same and the aforementioned analyses are robust.

5 Conclusion

The purpose of this article was to develop an agent-based model in order to explore the behaviors of the world energy system with bottom-up view. Considering the limitations of natural resources and interactions among geographical regions were the other objectives of the model. In order to consider the limitations of resources in the analysis, biophysical economics was introduced as the theoretical perspective of this research. With combination of biophysical economics and agent-based modeling, MRWEM was developed.

The first objective of the model was incorporating limitations of natural resources in the economic analyses. MRWEM is developed on the basis of biophysical economic paradigm. It incorporates the concepts such as URR and TP in the model design. Accordingly, it considers the decline in EROI of energy resources when they are extracted. As explained in section 4, the growth or decline of EROI can considerably influence the behavior of the energy sector in the model. So, the effects of limitations of natural resources on the behavior of the system can be explored and analyzed in MRWEM.

Moreover, one of the drawbacks of most existing global energy supply models is that they adopt a top-down view on the modeling process and analyses. The top-down view assumes that there is a centralized control over the behavior of the system. In MRWEM, the attributes and behaviors are defined at the level of regions and there is no centralized control in the world. This configuration enables a bottom-up analysis of the world. Having 11 geographical regions, MRWEM can also provide geographical insights about the system. The energy resources are not evenly distributed over the world. In addition, some regions consume more energy due to their state of economy. These diversities and differences necessitate different policies for development of regions. Having geographical insight about the world energy system next to biophysical insights can help policy makers to develop deliberate policies.

Another drawback of top-down models is that they cannot analyze the effects of regions and their interactions on the global emergent states and behavior of the system. MRWEM facilitates energy interactions and trade among regions. It is done by using the trade EROI function (Kauffman, 1986.) next to the dynamic EROI function(M. Dale, 2010). As explained in section 4, MRWEM can be used to explore the size and the network of energy trade among regions. It provides insights about the share of energy trade in the total energy consumption in the world. It can also show what type of behaviors can be seen in the future of energy trade such as peak and decline.

Finally, similar to top-down models like GEMBA, MRWEM can provide some insights about the possible peak and decline in production of most energy resources in the future. It warns about the increasing gap between real energy requirements of regions and energy production. Having sense about this phenomenon can motivate policy maker to reconsider current trends and policies. In addition, geographical analysis and insight form MRWEM can help policy makers to revise or customize policies for specific regions.

Future Research

MRWEM considers the energy price an exogenous variable. It assumes that there is no relationship between energy price, energy demand, and energy production. However, in the real world, these concepts are linked. The fact that the function of trade EROI uses energy price, can provide a great opportunity for improving MRWEM. Energy price can be the interface between MRWEM and standard economics models. It also enables analyzing results from multiple perspectives.

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